SEISMIC ISOLATION BOUNDING ANALYSIS: PROPERTY MODIFICATION FACTOR APPROACH OF ASCE 7-2016 AND ASCE 41-2017

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Abstract

The application of seismic isolation in the United States is regulated by Building Codes which invariably refer to Chapter 17 of ASCE 7 (the *Standard*) for the analysis and design requirements of new buildings and Chapter 14 of ASCE 41 for the retrofit of existing buildings. The *Standard* has evolved over the years to reflect the state of the art knowledge and practice in the field. The latest evolution, ASCE 7-2016, now includes a systematic procedure for establishing maximum and minimum probable values of bearing properties with due consideration for three categories of effects, namely: 1) aging effects and environmental conditions, 2) hysteretic heating and speed of loading effects, and 3) manufacturing variations.

This paper provides guidance to practicing engineers on the basis and implementation of the *Standard*, with respect to the property modification (λ) factors. These factors are used to define the isolation system properties that are used in separate upper- and lower-bound analyses, where the governing case for each response parameter of interest is used for design.

The determination of isolation system properties is illustrated for a lead-rubber and a concave sliding isolation systems. For each system, the following design scenarios were investigated: (a) assuming there is little qualification test data available and adopting default properties, and (b) using prototype test data of two bearings to calculate properties. Although these λ factors may be useful for similar systems, they are project-specific, manufacturer-specific and also dependent on the materials used, therefore cannot be merely adopted for other designs.

The requirements of ASCE 7-2016 have been largely replicated in ASCE 41-2017, with the intent being identical, thus for simplicity only one *Standard* (ASCE 7) is mentioned in this paper. Nevertheless, ASCE 41-2017 contains differences and further improvements on the *Standard* based on the work of the authors. The second author was involved in the revision of ASCE 7 and the first author was involved in the alignment of ASCE 41 provisions.

Keywords: seismic isolation; property modification factors; bounding methods of analysis; isolation system properties

1. Background

The concept of seismic isolation is not new and has not changed in the past 150 years, if not longer. The first US patent on a seismic isolation system was in 1870 by Jules Touaillon and was a double concave spherical-ball rolling system. What has changed is our capability to execute the concept using isolation hardware (isolators or bearings) which are more reliable and whose behavior can be predicted more accurately. This is the key to achieving our performance goals today, not to blindly apply the concept, but to have an intimate understanding of a bearing's behavior and ensure that this behavior is appropriately accounted for in analysis and design.

Seismic bearings have unique characteristics that are unfamiliar to most registered design professionals (RDP). Foremost they have variability and uncertainty in their properties which require thorough testing to quantify. This is because bearings are usually custom designed, are constructed using proprietary technologies and are made of non-traditional civil engineering materials like composites, lead and elastomers.

Extensive testing and implementation over the past three decades have advanced design practice significantly. Recent studies by Giammona et al. [1] have shown that the current assumptions and analysis methods used in practice can predict responses (displacements, forces) which closely match shake-table test data. Yet the behavior of practical isolation systems can be, and sometimes are, drastically different to that estimated in analysis. This is particularly prevalent if several complications of the technology are overlooked, specifically: **(1)** the lifetime behavior of the isolation hardware (changes over time, environmental conditions), **(2)** modelling of hardware to describe instantaneous behavior (effects of heating and speed of loading during seismic motion) and **(3)** proper manufacturing and testing of hardware. All of which concern the bearings behavior and emphasize why the selection of their properties is an intricate input for the analysis

In this regard, the analysis by Giammona et al. had an unfair advantage because the chosen friction coefficient of the bearings was calibrated after viewing shake-table test data. This is not the case in practice, and instead we use bounding procedures to envelope the likely response. Interestingly the target friction coefficient for Giammona et al. was 8%, however unidirectional sinusoidal cyclic testing of all the bearings showed an average value closer to 10% (1.25 factor of difference) and only through *posterior* calibration (not available for real-life applications) was the first cycle value of 11% chosen (1.4 factor of difference), as it gave the best agreement with shake-table test data. This illustrates the complexity and uncertainty of determining properties, even for a quality manufacturer where all the bearings are tested and there are no environmental or aging effects.

Regulations for the construction of isolation hardware are sparse, as there is no official certification required of manufacturers and no governing rules for the production and assembly of bearings. These details vary by manufacturer and are usually proprietary. Hence there can be a considerable difference in the quality and performance of different bearings, even for identical bearing types produced by different manufacturers. US Building Codes invariably refer to Chapter 17 of ASCE 7 (the *Standard*) [2] for analysis and design requirements of seismically isolated buildings. By default, this *Standard* gives governing design and testing requirements for the isolation hardware and addresses the uncertainty and variability in their properties (i.e. the three complications described previously). Past versions of the *Standard* had little guidance on how to account for variations in bearing properties, apart from roughly stating that it should be considered in analysis. The latest evolution, ASCE 7-2016 [2], now explicitly requires bounding analyses and gives a systematic procedure for determining the upper- and lower-bound values of isolation system properties.

Bounding analysis procedures are used as a simplifying and practical approach to account for the statistical variation in bearing properties. Two analyses are necessary as either the maximum or minimum probable bearing properties may govern for design. For instance, an upper-bound analysis may govern the sizing of the building frame whereas a lower-bound analysis may govern the sizing of the isolation hardware and surrounding moat clearance. The decision on what properties to use for upper- and lower-bound analysis is achieved using a combination of test data, rational analysis and engineering judgement by means of the property modification factor approach.

2. Property Modification Factor Approach

The methodology of establishing upper- and lower-bound values for a bearings properties based on property modification (λ) factors was devised by Constantinou et al [3] and first implemented into Standards which govern the design of seismically isolated bridges in 1999 [4]. The utility of the approach is in addressing a complicated statistical problem. It can be likened to the capacity-design method whereby the structure is designed for the probable properties of the ductile mechanism (the isolation system) so that (a) inelastic action and energy dissipation is confined to the ductile mechanism and (b) the ductile mechanism is stable and can accommodate large displacements.

The complexity is that the ductile mechanism of seismically isolated structures requires assessment of not only the upper probable value of properties, but also the lower probable value and that the properties of bearings are (sometimes highly) variable and uncertain. Their properties vary over time and vary due to the occurrence of independent events, so their exact state is unknown when the controlling earthquake occurs. They also vary and degrade during the earthquake itself, with the extent being dependent on the characteristics of the seismic hazard, site and isolation system. Moreover, the properties of each bearing are not identical, but have a distribution in properties where the dispersion is dependent on the construction protocols unique to each manufacturer. The problem is thus project-specific and manufacturer-specific as well dependent on the type of materials used.

One approach is to conduct a statistical analysis of the distribution of properties and likelihood of the occurrence of relevant events, including the controlling earthquake. However, a simpler and more practical procedure is to consider the impact of each event (say aging, contamination, etc.) on a case-by-case basis and quantify how it changes the nominal force-displacement behavior (or mechanical properties) in the form of two property modification (λ) factors: $\lambda_{max} \geq 1.0$ and $\lambda_{min} \leq 1.0$. Then all the maximum or minimum λ factors can be combined, with some adjustment, to form an envelope of behavior.

The first step involves deciding on the bearing force-displacement model and what parameters dictate behavior. Contemporary bearings can be idealized as a bilinear model consisting of the characteristic strength, Q_d, and post-elastic stiffness, k_d, (with effective stiffness, K_M) as shown in Fig. 1. By relation, these parameters are dictated by certain properties and the geometry of the bearing. For a lead-rubber bearing, the basic mechanical properties of interest are the effective yield stress of lead, σ_{YL}, which effects Q_d and the shear modulus of rubber, G, which effects k_d.

The next step involves setting some specific definition to compute a single, "nominal" value of these mechanical properties. This is usually a fresh and unscragged bearing (the bearing has not been previously tested so is virgin), tested at an ambient temperature of 20°C and under specific conditions of vertical load, strain (or displacement), frequency (or velocity of loading), and averaged for a certain number of loading cycles.

Then we consider each event to see its effect on the nominal value. For example, the event of aging in LR bearings may cause an increase in k_d (or G) of 20% from the nominal value so is given factors $\lambda_{aging,max,kd,} = 1.2$ and $\lambda_{aging,min,kd} = 1.0$. The process is done independently for each mechanical property for all plausible events that cause a measurable change in the nominal value. All the maximum or minimum λ factors for each event are then multiplied together as shown in Eq. (1) or Eq. (2), respectively, to get overall maximum and minimum λ factor for each mechanical property.

$$\lambda_{max,property} = 1 + f_a \times ((\lambda_{event\ 1,\ max,\ property} \times \lambda_{event\ 2,\ max,\ property} \times \ldots \lambda_{event\ N,\ max,\ property}) - 1) \quad (1)$$

$$\lambda_{min,property} = 1 + f_a \times (1 - (\lambda_{event\ 1,\ min,\ property} \times \lambda_{event\ 2,\ min,\ property} \times \ldots \lambda_{event\ N,\ min,\ property})) \quad (2)$$

Obviously the multiplication of λ factors from different events may result in a system factor that is very conservative. That is, the probability of several additive effects (i.e. maximum aging and contamination, lowest temperature, etc.) occurring simultaneously with the governing earthquake is considered very small. Therefore, the product of λ factors is modified using the adjustment factor, f_a, as shown in Eq. (1) and Eq. (2). Constantinou et al. [3] recommend adjustment factors of 1.0, 0.75 or 0.66 depending of the significance of the structure.

The overall $\lambda_{max,property}$ and $\lambda_{min,property}$ are then applied to its nominal value for every mechanical property to form upper- and lower-bound force-displacement models, respectively, as shown in Fig. 1.

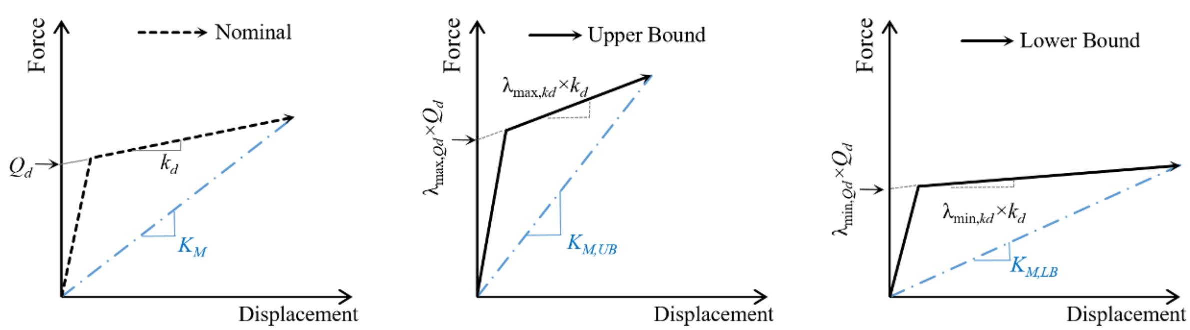


Fig. 1 – Illustration of the property modification approach to bilinear bearing model

Over the years the utility of the λ factor approach has expanded. Initially the focus was on the lifetime behavior of the bearings due to aging and environmental events such as contamination, extreme temperatures, cumulative travel (due to movement of the structure), etc. The significance of which are greater for bridges due to the exposed environment and types of loadings (i.e. traffic, thermal movements). Hence, the approach was introduced into AASHTO [4] 17 years ago. For the latest building *Standard*, the approach now explicitly defines two other categories of effects, namely the variations that occur during seismic motion and manufacturing tolerances. Specifically, the three categories of λ factors (or events) in the *Standard* are:

- **λ_{ae}** which encompasses aging and environmental effects. These are events that occur over the design life of the bearing and include aging, contamination, extreme ambient temperatures, creep, cumulative travel/history of loading, etc.
- **λ_{test}** which encompasses variations observed during testing which are not explicitly captured in the analysis model. These are events that occur during the seismic excitation and include hysteretic heating effects, frequency/speed of loading effects, first-cycle effects such as scragging, vertical load, etc.
- **λ_{spec}** which encompasses specification tolerances. This is the event of using properties based on a small number of prototype (or similar) bearings, since the nominal properties of the larger population of production bearings will be different due to manufacturing variations.

In the *Standard*, Eq. (1) and Eq. (2) is replicated into the three groups of events (or λ factors) as shown in Eq. (3) and Eq. (4), respectively. Here the system adjustment factor, f_a, is set to 0.75 for the aging and environmental effects and is set to 1.0 for the testing and specification λ factor groups. The rationale being that full aging and contamination will not be realized when the controlling earthquake occurs.

$$\lambda_{max,property} = (1 + 0.75(\lambda_{ae,max,property} - 1)) \times \lambda_{test,max,property} \times \lambda_{spec,max,property} \geq 1.8 \quad (3)$$

$$\lambda_{min,property} = (1 - 0.75(1 - \lambda_{ae,min,property})) \times \lambda_{test,min,property} \times \lambda_{spec,min,property} \leq 0.6 \quad (4)$$

The *Standard's* limits of 1.8 and 0.6 in Eq (3) and Eq. (4), respectively, in fact should rarely be used and tighter bounds are usually specified. This is because the limits only apply to inexperienced manufacturers with little/no test data, and in any case, it is implied by the *Standard* that more testing would be required. Hence the default limits are only indicative and, although wide, may not be conservative for untested products.

Although it is expected that manufacturers conduct their own testing and establish λ factors for their products, the RDP must still be involved in their final specification. Interestingly, when the λ factor approach was first proposed in 1999 [3], it recommended that some agency should take responsibility for reviewing and approving the results of manufacturers. Since this has not yet eventuated, the RDP and the peer review panel have become the reviewers by default and, accordingly, must appreciate the behavior of bearings and their relevant property modifications.

This paper will now demonstrate the procedure for two predominant types of isolation systems: (a) *elastomeric* using lead-rubber (LR) bearings and (b) *concave sliding* using triple Friction Pendulum™ (FP) bearings. The geometry of the example bearings, which were used on actual projects, are contained in Table 1.

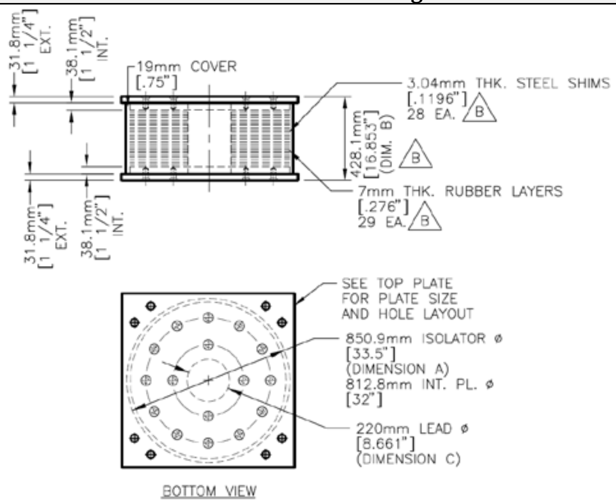
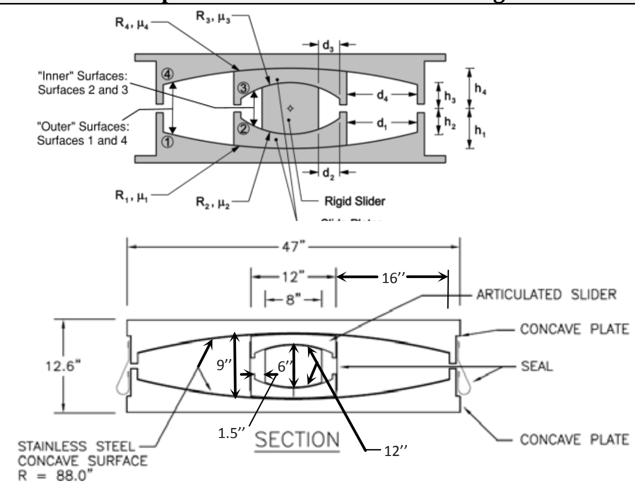
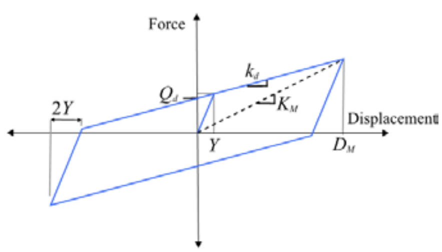
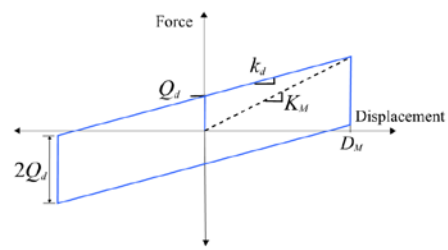
3. Behavior of Seismic Bearings

The analytical models used in analysis are simplifications of a complex nonlinear behavior of the bearings. The basic force-displacement models adopted for the example LR and FP bearings, along with their specifics, are given in Table 1. The types of events or effects which cause changes in their mechanical properties are outlined in terms of λ-factor groups in Table 2. For a more thorough background, the RDP should study the latest in knowledge [7] and consult with manufacturers on the behavior of their products (i.e. review qualification data).

The $\lambda_{test,max}$ and $\lambda_{test,min}$ are related to the analytical model adopted for analysis. Typical software (SAP2000, ETABS) assume that the bearings properties remain constant throughout the earthquake record, whereas in reality they are instantaneously changing. For LR bearings, there are instantaneous changes due to scragging and speed of loading effects, and degradation due to heating effects on the lead core. For FP bearings, the friction coefficient varies during seismic motion due to velocity, compression contact pressure and heating effects. Hence bounding is necessary to envelope properties when not explicitly accounted for in the analysis model.

More advanced force-displacement models exist which may be important for beyond MCE_R displacements or if residual displacements or in-structure accelerations are of interest [5]. The most sophisticated analytical models are able to explicitly capture instantaneous effects, such as heating on the lead core [6], and reduce the need for λ_{test} factors altogether (i.e. $\lambda_{test,max}$ and $\lambda_{test,min}$ closer or equal to 1.0). It is also possible, but uncommon, to have $\lambda_{spec,max}$ and $\lambda_{spec,min}$ equal to unity if all the production bearings are constructed and tested (so their properties are known) before analysis and design. Nevertheless, bounding analysis is likely to remain for the foreseeable future since advanced analyses and off-the-shelf bearings are not common practice and because aging and environmental effects (λ_{ae}) need to be accounted for.

Table 1 – Details of example bearings and simplified force-displacement models

	Lead-Rubber Bearing	**Triple Friction Pendulum™ Bearing**[2]
Dimensions of Bearing Units		
Force-Displacement Models		
Equations	Characteristic strength[1]: $Q_d = \frac{\pi D_L^2 \sigma_{YL}}{4}$ (5) Post-elastic stiffness: $k_d = \frac{G f_L \pi (D_B^2 - D_L^2)}{4T_r}$ (6) Energy dissipated per cycle: $E_{loop} = 4Q_d(D_M - Y)$ (7) Effective stiffness: $k_{eff} = k_M = \frac{Q_d}{D_M} + k_d$ (8)	Characteristic strength: $Q_d = \mu W$ (9) Post-elastic stiffness: $k_d = \frac{W}{2(R_1 - h_1)} = \frac{W}{2R_{eff}}$ (10)
Parameters	D_L = Diameter of the lead core = 8.66 inch f_L = effect of the lead core on k_d. Only after repeated cycling is the factor equal to 1.0 D_B = Diameter of the bearing = 32 + ½ cover = 32.75 inch T_r = Total thickness of rubber layers = 8.0 inch Y = Yield displacement which is about 0.25-1.5 inch D_M = Maximum Considered Earthquake (MCE_R) displacement K_M = Effective stiffness at MCE_R displacement **Basic Mechanical Properties[3]:** σ_{YL} = Effective yield stress of lead (ksi) G = Shear modulus of rubber (ksi)	R_i = Radius of curvature of concave plates (inch) d_i = Nominal displacement capacity (inch) h_i = Height to pivot point (inch) R_{eff} =Effective radius = 83.5 inch W = Weight on bearing (kip) **Basic Mechanical Properties[3]:** μ = Coefficient of friction

1. Eq. (5) implies that any contribution to the strength from rubber is included in σ_{YL}, which is a reasonable simplification for low-damping rubbers used in LR bearings.
2. Bearing is symmetrical about mid-height: $R_1 = R_4 >> R_2 = R_3$, $\mu_2 = \mu_3 < \mu_1 = \mu_4$, $d_1 = d_4$ & $d_2 = d_3$, $h_1 = h_4$ & $h_2 = h_3$
3. These are the basic mechanical properties of interest for developing λ factors. Other parameters could be included for more sophisticated analyses.

Table 2 – Brief introduction on types of property modifications (λ-factors)

Events/Effects	**LR Bearing Mechanical Properties**		**FP Bearing Mechanical Properties**
	σ_{YL} (Lead)	*G* (Low-damping rubber)	μ (Unlubricated interface[1])
Aging Effects and Environmental Conditions – $\lambda_{ae,max}$ and $\lambda_{ae,min}$			
Aging effects	Lead made with 99.99% purity does not experience aging (at least within the lifetime of a typical structure)	Depends on the rubber compound, bearing size and quality of vulcanization and curing. Related to scragging[2]. Order of 10-30% increase in *G*.	Complex and refers to corrosion. It depends on the orientation of the sliding interface, environmental exposure and composition and materials of sliding interface. Increases μ.
Contamination	As with aging, it is not a concern.	Contamination does not apply.	Complex and refers to third-body effects and abrasion of the sliding surface. Increases μ.
Ambient temperature	A concern if the bearings are in an exposed environment where the expected temperature falls well below freezing for a sustained duration. Bridges in cold climates are the usual candidates.		
Cumulative movement	A concern if the bearings continuously move under service loadings (i.e. wind). Bridges are the usual candidates as they have large cumulative movements due to traffic loading and thermal movements.		
Creep	Not a concern.	Does not affect *G*. Needs to be accounted for and limited by proper selection of materials and limiting load.	Does not affect μ. Needs to be accounted for in confining the softer material of the sliding interface.
Fatigue	Not a concern.	Does not affect *G*. Typically accounted for by limiting shear strain in rubber.	Not a concern.
Wear	Not a concern.	Not a concern.	Important in bearings used in bridges where testing needs to demonstrate acceptable wear in cumulative travel. Need to test dynamically in realistic conditions to assess wear for seismic conditions.
Testing Variations – $\lambda_{test,max}$ and $\lambda_{test,min}$			
First-cycle effects	Lead core may contribute to stiffness in initial cycles.	Scragging[2] results in a lower *G* in second and beyond cycles. Studies [7] show that full recovery of virgin properties in 'scragged' bearings is highly likely. Depends on similar factors as aging. Effects can be significant and are greater for softer (low modulus) rubbers.	The softer material of the sliding interfaces leaves a film on the stainless steel which decreases μ. This is more pronounced for uni-directional testing whereas actual earthquake traces may have little overlap with travelled areas.
Heating effects	Hysteretic heating causes a reduction in σ_{YL}. This can be significant but is recoverable after a short time. Validated theory can quantify effects [6].	Need not be considered. The rise in temperature is minor [7].	Frictional heating effect causes wear and a reduction in μ. The temperature increase is proportional to heat flux (a function of μ, sliding velocity and compressive stress).
Velocity/strain-rate effects	Has a significant effect on the initial value of σ_{YL}. Slow-speed testing underestimates the starting value of σ_{YL}	Minor effects which are captured in dynamic testing of bearings.	Influences μ due to a) μ being dependent on velocity and b) frictional heating. At high velocities μ tends to be invariable (but for the effect of heating).
Vertical compression stress	Contributes to the confinement of the lead core hence effects $\sigma_{YL.}$	Minor effects which are captured in dynamic testing of bearings.	Increases in slider contact pressure decrease μ and tend to reach a constant value at high pressures. Also influences μ through heating.
Specification Tolerance – $\lambda_{spec,max}$ and $\lambda_{spec,min}$			
Variability in production bearings properties which on the average differ from the properties measured in prototype testing.	Manufacturing details such as the method of installing the lead core, bearing size and details for steel shims affect confinement of lead core and hence values of σ_{YL}. Highly dependent on the quality and control processes of the manufacturer.	Rubber compounds, vulcanization and curing may vary between batches and hence affect *G*. Highly dependent on the quality and control processes of the manufacturer.	Different batches of materials and manual procedures such as bonding of the softer material of the sliding interface are susceptible to variations in μ. Dynamic testing is very important to check quality and properties for sliding bearings.

1. Consists of unlubricated and sealed highly polished austenitic stainless steel in contact with a softer material which may contain PTFE (polytetrafluoroethylene) and other materials and glue.
2. Scragging is the temporary degradation in properties with repeated cycling. Most pronounced in the first cycle of loading and is believed to be due to incomplete curing and continuing chemical processes in rubber, hence is recoverable and related to aging.

4. Determination of Nominal Properties and λ Factors

4.1 Default Lead-Rubber Bearing Properties

The two mechanical properties to determine, per Table 1, are σ_{YL} and *G*. There is uncertainty in σ_{YL} as it depends on the rate of strain, size and confinement of the lead core, manufacturing processes and degrades from cycle to cycle due to heating effects. But in general it is in the range of 1.45 to 1.75ksi for a high speed, large amplitude motion averaged over three-cycles [8]. Using the *Standards* default factors $\lambda_{spec,max}$=1.15 and $\lambda_{spec,min}$=0.85 gives a range of 1.36 to 1.84ksi (nominal value of 1.6ksi). Heating effects may be calculated based on theory [7], or by adopting the *Standards* default factors of $\lambda_{test,max}$=1.6 and $\lambda_{test,min}$=0.9. As described in Table 2, aging and environmental effects on lead are not a concern, so $\lambda_{ae,max}$=$\lambda_{ae,min}$=1.0.

The nominal value of *G* depends on the rubber compound and manufacturing processes, as well as frequency and conditions of testing. The lowest *G* values are around 65psi [8] however there is uncertainty in this value so adopt $\lambda_{spec,max}$=1.15 and $\lambda_{spec,min}$=0.85. Few manufacturers are capable of producing low modulus rubber without significant scragging effects (see Table 2). It is preferred to establish factors by project testing or materials qualified in the past since the *Standards* default values of $\lambda_{test,max}$=1.3 and $\lambda_{test,min}$=0.9 may not be conservative. Aging in low-damping rubber generally has small effects, provided scragging is also minor, thus $\lambda_{ae,max}$=1.3 and $\lambda_{ae,min}$=1.0. The overall λ_{max} and λ_{min} values are given in Table 6.

The *Standards* default λ-factors are very conservative for reputable manufacturers. More appropriate would be to consider narrower ranges based on the review of qualification test data, as described in the following.

4.2 Prototype Testing of Lead-Rubber Bearings

Two virgin, full-scale prototype LR bearings (see Table 1) are subjected to three cycles of high-speed (effective period of 3.0sec, peak velocity of 40inch/sec) unidirectional sinusoidal displacement at an amplitude (D_M) of 19.1inch with average compression load of 830kip (D + 0.5L) and ambient temperature of 20°C. The force-displacement behavior of each bearing is plotted in Fig. 2. The peak force and displacement and energy dissipated per fully-reversed cycle (calculated by numerical integration) are stated in Table 3.

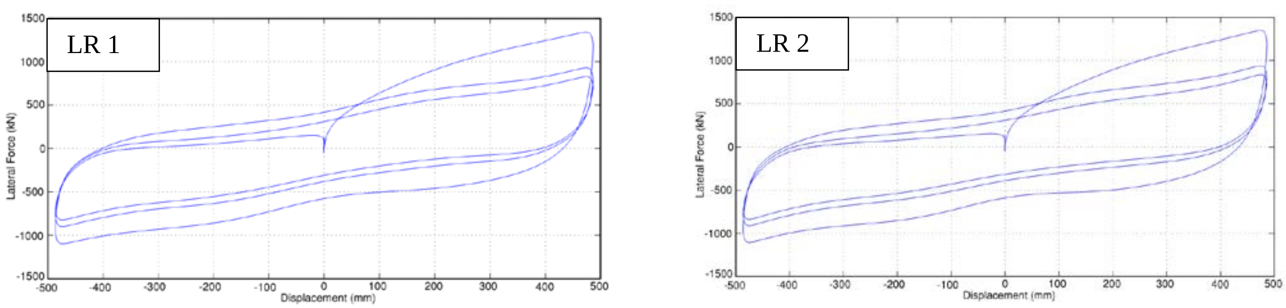


Fig. 2 – Dynamic test data of two prototype LR bearings (1inch = 25.4mm, 1kip = 4.45kN)

Table 3 – Test data for two prototype LR bearings

Measure	F^+ (kip)	F^- (kip)	Δ^+ (inch)	Δ^- (inch)	E_{loop} (kip-inch)
LR 1 Cycle 1	303	-248	19.1	-19.2	9915
LR 1 Cycle 2	211	-205	19.1	-19.1	6799
LR 1 Cycle 3	188	-188	19.1	-19.1	5405
LR 2 Cycle 1	301	-246	19.1	-19.1	9818
LR 2 Cycle 2	209	-202	19.1	-19.1	6733
LR 2 Cycle 3	186	-185	19.1	-19.1	5364

Curve/model fitting of this data requires judgement. The *Standards* basic approach to determine the force-displacement characteristics is illustrated in Table 4 (see [6] for different approach). The nominal values are averaged over three cycles, and averaged for the two bearings, giving σ_{YL} = 1.68 ksi and *G* = 61 psi. These properties should be determined from the initial tests, of a regime of many tests (that have short rest intervals), to avoid residual heat which contaminate data. Since these bearings are tested from a virgin state, this is not a concern.

Table 4 – Determination of properties for LR bearings

Measure	k_{eff} **(**K_M**)**	D_M	Y	Q_d	σ_{YL}	k_d	f_L	G	β_{eff}
Units	kip/inch	inch	inch	kip	ksi	kip/inch	-	psi	-
Calculation Method	Std[1] Eq. 17.8-1	Average	Fitted	Eq. (7)	Eq. (5)	Eq. (8)	Assumed	Eq. (6)	Std[1] Eq. 17.8-2
LR 1[1] Cycle 1	14.4	19.15	0.6	133.6	2.27	Discard			0.30
LR 1 Cycle 2	10.9	19.1	0.6	91.7	1.56	6.07	1.0	62	0.27
LR 1 Cycle 3	9.8	19.1	0.6	72.9	1.24	6.02	1.0	61	0.24
LR 1 Avg.					**1.69**			**61.5**	
LR 2[1] Cycle 1	14.3	19.1	0.6	132.3	2.25	Discard			0.30
LR 2 Cycle 2	10.7	19.1	0.6	90.8	1.54	5.99	1.0	61	0.27
LR 2 Cycle 3	9.7	19.1	0.6	72.3	1.23	5.90	1.0	60	0.24
LR 2 Avg.					**1.67**			**60.5**	
Nominal					**1.68**			**61**	

1. Definitions: Std. = ASCE 7-2016 *Standard* per [2], LR 1 & 2= Lead-rubber bearing 1 and 2 per Fig. 2.

The next step is to determine associated λ values. The near identical properties of the two bearings is fortuitous, but may justify using tighter manufacturing tolerances of $\lambda_{spec,max}$**=1.10 and** $\lambda_{spec,min}$**=0.9** (see Section 4.4 for more discussion), although this assumption should also be accompanied with tighter acceptance criteria for the production bearings.

For **rubber (*G*)**, additional data is required to determine the scragging effects. This is because the heating effects of lead mask behavior in the first cycle (i.e. $f_L > 1.0$), thus this cycle is not used to determine *G*. Qualification data on scragging effects should always be from virgin, never before tested bearings, even if it is the manufacturers protocol to 'scrag' the bearings. This is because it is highly likely that the virgin properties will fully recover within a few months [7] and thus should be included in analysis. Coupon tests may also quantify scragging however size effects should be taken into consideration since large bearings exhibit more variable zones of curing through the volume compared to small coupon samples. Based on a review of this quality manufacturers data a scragging factor (traditionally defined as the first to third cycle stiffness) of 1.2 is appropriate. This factor is not reduced (to first cycle divided by nominal) since the nominal value is based on the average of the last two cycles, which have little difference. Hence $\lambda_{test,max}$**=1.2 and** $\lambda_{test,min}$**=1.0**. The aging and environmental behaviors are permitted to be based on bearings not meeting similarity requirements of the *Standard*. Considering good aging characteristics given the low scragging factor, it is reasonable to consider an aging factor of 1.1. Thus assuming the bearings are in a conditioned space and do not continuously move under service loadings, the values of $\lambda_{ae,max}$**=1.1 and** $\lambda_{ae,min}$**=1.0** are appropriate.

For **lead (**σ_{YL}**)**, the upper-bound testing factor is taken as the first cycle properties divided by the nominal value giving $\lambda_{test,max}$=2.26/1.68=**1.35**. Since the testing is dynamic, velocity effects are already included and the λ_{test} factors only encompass heating. What to take for the lower-bound is not clear in the *Standard*. In the initial cycles of loading the lead loses strength due to hysteretic heating effects. This reduction in strength is temporary and recoverable with adequate cooling time. The data in Table 4 show a large difference between the σ_{YL} in the first and third cycles, which is not unusual for large-scale bearings tested at high-speed. It is the opinion of the authors that the lower bound should be based on considerations of the seismic hazard and isolation system properties (strength and stiffness). Equivalent energy response history analysis studies [10] demonstrate that about two fully-reversed cycles at D_M are expected for isolation systems with a yield strength to supported weight ratio (Q_d/W) of ≥0.06 and period based on a post-elastic stiffness of ≥2.5 seconds. Therefore the lower-bound will be taken as the second cycle properties, giving $\lambda_{test,min}$=1.55/1.68=**0.92**. Soft-soil sites and large-magnitude earthquakes may warrant more cycles. As discussed in Table 2, $\lambda_{ae,max}$**=** $\lambda_{ae,min}$**=1.0**. Note that any contribution to the strength from low-damping rubber was considered insignificant (and we incorporated it in σ_{YL}), however this would not be the case if the bearings were exposed to low temperatures.

The *Standard* also requires consideration of variation in vertical load and to envelope behavior from $0.5D_M$ to $1.0D_M$ which requires further test data. We will assume that the k_M and β_M averaged for the three load combinations (D+0.5L, max, min) does not differ by more than 15% from k_M and β_M based on D+0.5L and thus will not bound vertical load. This recognizes that the mechanical properties of the isolation system are not (materially) affected by fluctuations in the axial load on individual bearings. Rather, the behavior is determined by the average load on the isolation system (all bearings), which is near D+0.5L. However, the effect of varying axial load on the properties of individual bearings is of interest as it affects the design of the bearing and of the structure in the vicinity of that bearing. Variations in displacement amplitude effect G (dependent on shear strain) and heating effects on σ_{YL}. It is the opinion of the authors that the testing at $1.0D_M$ should primarily be used for determining properties and bounds, since the *Standard* has a MCE_R-only basis for design. The behavior at other displacement amplitudes can viewed to verify consistent with the MCE_R model and need only be a best-fit.

This dynamic test data may be used determine dynamic properties for other projects and the *Standard* is intentionally broad so that this can occur. The key requirements are that bearings are made of the same materials, under the same quality and control procedures by the same manufacturer (i.e. same plant) and that principles of scaling and similarity (e.g. [6]) are followed. For example, heating calculations [6] can be used to determine the nominal and λ_{test} factors for a project that requires similar bearings but has a smaller D_M of 15 inches. Performing heating calculations is complex and requires the solution of a differential equation. However, if heat conduction through the shim and end steel plates is neglected (valid for few cycles of high speed motion), the effective yield strength σ_{YL} can be obtained by this simplified theory:

$$\sigma_L = \frac{\sigma_{L0}}{1 + \dfrac{E_2 \sigma_{L0} S}{\rho_L c_L h_L}} \tag{11}$$

In (11) σ_{L0} is the effective yield stress at initiation of motion (at time t = 0), S is the cumulative distance travelled, ρ_L is the density of lead (11,300 kg/m^3), c_L is the specific heat of lead (130 Joule/(kg °C)), h_L is the height of the lead core (29×7mm+28×3.04mm=0.288m), and E_2 is a material property of lead (0.0069/°C). Eq. (11) shows that the instantaneous yield stress of lead is related to the ratio of the distance travelled to height of lead core and the initial value σ_{L0} in a complex nonlinear relationship. The σ_{L0} value is back-calculated based on the test data and Eq. (11) as shown in Fig. 3(a) (also see [5]) to obtain a starting value of 3.1ksi. This value can be used in Eq. (11) for other projects to predict properties and bounds as shown in Fig 3(b). For a D_M of 15inch (S=60inch per cycle), the predicted nominal σ_{YL} is (2.45+1.73+1.33)/3=1.83ksi with $\lambda_{test,max}$=2.45/1.83=1.34 and $\lambda_{test,min}$=1.73/1.83=0.94. This range can be widened by the RDP for uncertainty in the starting value σ_{L0} if the similar bearing is of a different height, lower vertical load or slightly different testing frequency.

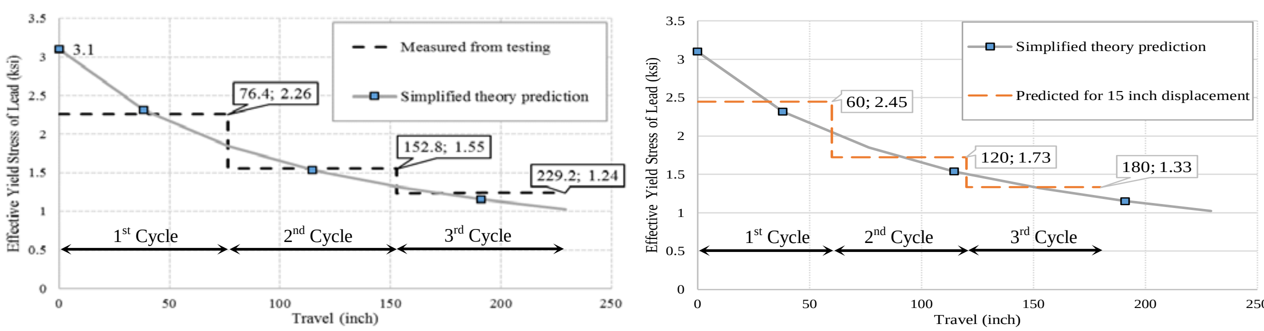


Fig. 3 – (a) Application of heating theory to test data (b) Prediction of strength for another project (D_M=15inch)

The *Standards* test specimen adequacy criteria are not checked in this paper, but a review in [5] demonstrates that the criteria are not met. It is assumed that the *Standards* exception applies (i.e. the limits may be adjusted). See the discussion in [5] and Ch14 of ASCE 41-2017 [10] for revisions.

4.3 Default Concave Sliding Bearings Properties

Theory, Eq. (10), predicts the post-elastic stiffness very well and since most manufacturers can achieve a high degree of geometric precision, the bounding of k_d for FP bearings is not warranted. Thus, the coefficient of friction, μ, is the only mechanical property of interest. The value of μ is affected by a number of parameters, of which sliding velocity, contact pressure (axial load divided by the contact area of the slider) and temperature are the most important. Furthermore, μ depends on the materials and construction of the sliding interface, which is manufacturer specific and proprietary. Thus a range of default μ values is not stated. Rather it is recommended to utilize dynamic qualification data from the manufacturer. For example, the three-cycle average μ for one manufacturer using a PTFE-stainless steel interface can be approximated based on [8] using μ=0.122-0.01×contact pressure (ksi). Hence for a 600kip load, the pressure is 5.3ksi, μ=0.122-0.01×5.3ksi = 0.069 less 0.015 for high velocities = 0.054 and then rounded to 0.05. The associated default λ factors from *Standard* commentary would be λ_{aging}=1.3 and $\lambda_{contamin}$=1.2, which after combination and adjustment gives 1+0.75(1.3×1.2-1) =1.42 along with $\lambda_{ae,min}$=1.0. The other default factors are $\lambda_{test,max}$=1.3 and $\lambda_{test,min}$=0.9, and finally $\lambda_{spec,max}$=1.15 and $\lambda_{spec,min}$=0.85, with the overall combinations in Table 6.

4.4 Prototype Testing of Concave Sliding Bearings

Two full-scale prototype FP bearings are subjected to three cycles of high-speed unidirectional displacement at variable amplitudes of about 1.0, 0.67 and 0.33 times D_M with average compression load of 600kip (D + 0.5L) and ambient temperature of 20°C. This testing is similar but not identical to the 1.0, 0.67, 0.5 and 0.25 times D_M required by the *Standard*. The force-displacement behavior of each bearing is plotted in Fig. 4. The displacement, normalized force and normalized energy dissipated per fully-reversed cycle are stated in Table 5.

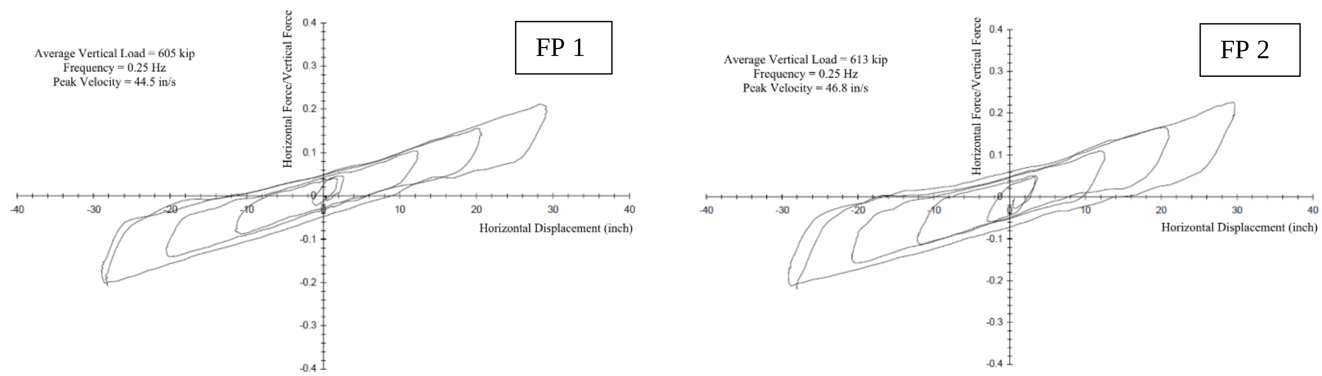


Fig. 4 – Dynamic test data of two prototype FP bearings

Table 5 – Test data and properties for two FP bearings

Measure	**Lateral Force/W**	**Displacement**	**E_{loop}/W**	**k_{eff}/W**	**μ**	**β_{eff}**
Units	kip/kip	inch	kip-inch/kip	kip/inch/kip	-	-
Calculation Method	Average	Average	Numerical integration	Std[1] Eq. 17.8-1	Eqs. (7) & (9)	Std[1] Eq. 17.8-2
FP 1 Cycle 1	0.207	29.0	6.236	0.00714	0.054	0.17
FP 1 Cycle 2	0.149	20.5	3.250	0.00725	0.040	0.17
FP 1 Cycle 3	0.096	11.8	1.405	0.00817	0.030	0.20
FP 1 Average					**0.041**	
FP 2 Cycle 1	0.219	29.3	7.888	0.00749	0.067	0.20
FP 2 Cycle 2	0.162	20.8	4.178	0.00780	0.050	0.20
FP 2 Cycle 3	0.112	12.2	2.102	0.00918	0.043	0.25
FP 2 Average					**0.053**	
Nominal					**0.047**	

1. Definitions: Std. = ASCE 7-2016 *Standard* per [2], FP 1 & 2= triple Friction Pendulum™ bearing 1 and 2 per Fig. 4.

The FP bearing in Table 1 actually has two different friction coefficients, μ_1 for the outer surfaces and μ_2 for the inner surfaces. However, the μ calculated in Table 5 is often used in practice since it can be readily obtained from E_{loop} by assuming Y=0. The difference between μ and μ_1 on the outer surfaces is generally small for large amplitude of motion. The nominal value is averaged over the three cycles, and for the two bearings to give μ=0.047. The $\boldsymbol{\lambda}_{\mathbf{test,max}}$ is taken as the ratio of the first cycle to nominal value **=** 0.061/0.047=**1.30**. The lower bound is calculated differently to the LR bearing since the testing is at different displacement amplitudes. The movement for the FP bearing during testing after 3 cycles is similar to the LR bearing after 2 cycles. Hence the lower bound test factor will be based on the third cycle properties, giving $\boldsymbol{\lambda}_{\mathbf{test,min}}$=0.037/0.047=**0.79**.

Aging and contamination are both complex phenomena (see Table 2 and [7]). For properly designed bearings with exposure time of 30 years and Type 304 stainless steel, λ_{aging}=1.1. Contamination depends on the orientation of the sliding surface (facing up or down) and is complicated by multiple sliding surfaces. Per [5] a $\lambda_{contamin}$=1.05 and $\boldsymbol{\lambda}_{\mathbf{ae,max}}$=1.1×1.05=**1.16**, which after adjustment is 1.12. The bearings are assumed to be in conditioned space and have little movement under service loading, thus $\boldsymbol{\lambda}_{\mathbf{ae,min}}$**=1.0**.

Bearings FP 1 and FP 2 seem to have quite different properties. This brings up the question on what would be the variability in properties from bearing to bearing in a large group of bearings and the relation of the average properties of the large group to the average properties of the two prototype bearings. An example is provided to illustrate the property variation over a large group of bearings. Among the several production data sets available, data exist for a group of 42 production bearings tested under three cycles of motion at about 15inch amplitude and 300kip load. This testing was also conducted on the prototype bearings FP 1 and 2 (but is not shown is this paper, see [5]), which showed three-cycle average μ values of 0.054 and 0.07, respectively with a 0.062 nominal value. The three-cycle average μ value of all the production bearings is shown in Fig 5, and is 0.0573. Hence the nominal value of the two prototype bearings is within 8% (0.062/0.573) of the tested average value of the production bearings and thus $\boldsymbol{\lambda}_{\mathbf{spec,max}}$**=1.10 and** $\boldsymbol{\lambda}_{\mathbf{spec,min}}$**=0.9** would have been appropriate, even though the two prototype bearings indicated more variation. Given that the average behavior of the bearings is important and not that of individual bearings, the specification tolerance for individual bearings may be wider say ±15-20%, but this should be taken into account in the design of connections and supporting structure.

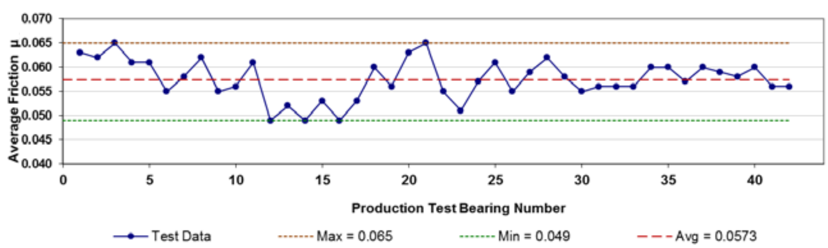


Fig. 5 – Three-cycle average μ of 42 production FP bearings under 300kip load

5. Summary

The three categories of λ factors and overall λ_{max} and λ_{min} are summarized in Table 6. They were determined for both LR and FP bearings and for two scenarios (a) adopting default λ factors and (b) using manufacturer specific prototype and qualification test data. The ratio of λ_{max} over λ_{min} was reduced by 34-48% by using prototype data.

The difference between model upper- and lower-bounds and a comparison to LR 1 test data is given in Fig. 6 for both default and prototype λ factors. The displacements are calculated using the ELF procedure using a hypothetical isolation system with 20 LR bearings, W=17,000kip and spectral acceleration S_{M1}=0.9. The same comparison is given for the FP bearings in Fig. 7, using FP 2 test data and assuming 20 FP bearings, W=12,000kip and S_{M1}=0.9. Note that the variance between the FP model and test data post-elastic stiffnesses are due to changes in μ, not k_d, because a) fluctuation of the vertical load during the tests (294 to 897kip for FP 1 and 282 to 920kip in FP 2) affect the instantaneous value of the μ, and b) heating effects affect μ and are more pronounced in the highest velocity, largest amplitude cycle. Thus to accept that k_d does not vary and assign any variability from cycle to cycle to μ is a satisfactory approach. To give an indication of the level of improvement in design parameters, the ratios of $D_{M, Default}$ over $D_{M, Prototype}$ and base shear $V_{b, Default}$ over $V_{b, Prototype}$ are 1.33 and 1.19 for the LR isolation system, and 1.08 and 1.04 for the FP isolation system, respectively.

Table 6 – Summary of λ factors for Default and Prototype Scenarios

	LR Bearing Mechanical Properties				**FP Bearing Mechanical Properties**	
	Default Q_d	**Default k_d**	**Prototype Q_d**	**Prototype k_d**	**Default Q_d**	**Prototype Q_d**
$\lambda_{ae,max}$	1.00	1.30	1.00	1.10	1.56	1.16
$\lambda_{ae,min}$	1.00	1.00	1.00	1.00	1.00	1.00
$\lambda_{test,max}$	1.60	1.30	1.35	1.20	1.30	1.30
$\lambda_{test,min}$	0.90	0.90	0.92	1.00	0.70	0.79
$\lambda_{spec,max}$	1.15	1.15	1.10	1.10	1.15	1.10
$\lambda_{spec,min}$	0.85	0.85	0.90	0.90	0.85	0.90
λ_{max} Eq. (3)	**1.84**	**1.83**	**1.49**	**1.42**	**2.12**	**1.60**
λ_{min} Eq. (4)	**0.60** (limit)	**0.60** (limit)	**0.83**	**0.90**	**0.60**	**0.71**
Ratio $\lambda_{max}/\lambda_{min}$	3.1	3.1	1.8	1.6	3.5	2.3

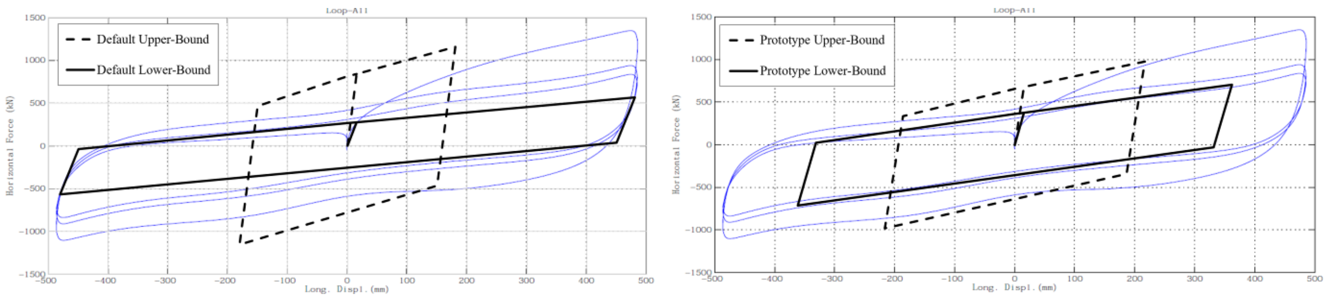


Fig. 6 – Comparison of default and prototype bounds to LR 1 test data for LR bearings

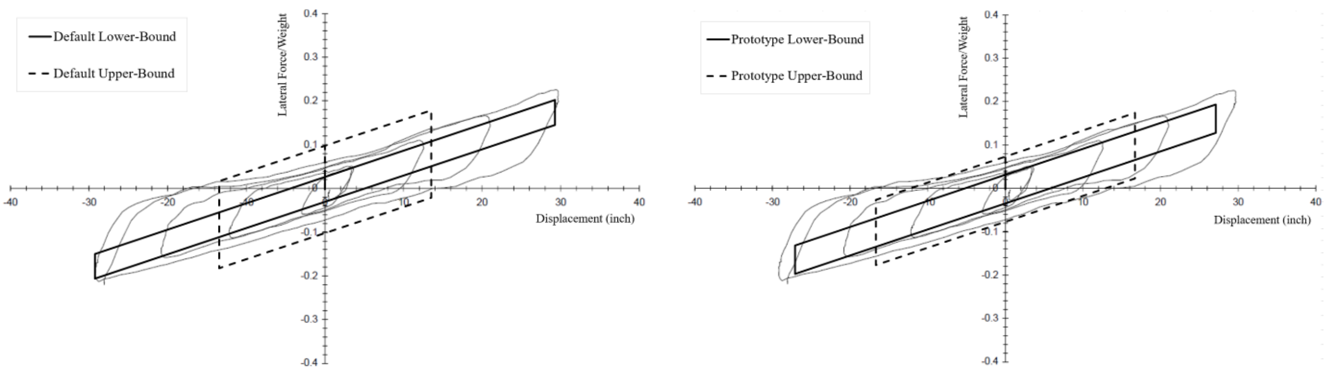


Fig. 7 – Comparison of default and prototype bounds to FP 2 test data for FP bearings

6. References

[1] Giammona A, Ryan K, Dao N (2015): Evaluation of assumptions used in engineering practice to model buildings isolated with triple pendulum isolators in SAP2000. *Earthquake Spectra*, Volume 31, No. 2, pages 637-660.

[2] American Society of Civil Engineers (2016). "Minimum Design Loads for Buildings and Other Structures", *ASCE/SEI 7*. Chapter 17 (Replacement) can be found in the "2015 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures", *FEMA P-1050-1*.

[3] Constantinou, M. C., Tsopelas, P., Kasalanati, A, Wolff, E. D. (1999). "Property Modification Factors for Seismic Isolation Isolators", *MCEER-99-0012*, MCEER, Buffalo, NY.

[4] American Association of State Highway and Transportation Officials (1999). "Guide Specification for Seismic Isolation Design", *AASHTO*, Washington, D. C.

[5] McVitty, W. J., Constantinou, M. C. (2015). "Property Modification Factors for Seismic Isolators: Design Guidance for Buildings", *MCEER-15-0005*, MCEER, Buffalo, NY.

[6] Kalpakidis, I. V., Constantinou, M. C., (2008). "Effects of Heating and Load History on the Behavior of Lead-Rubber Isolators", *MCEER-08-0027*, MCEER, Buffalo, NY.

[7] Constantinou, M. C., Whittaker, A. S., Kalpakidis, Y., Fenz, D. M. and Warn, G. P. (2007). "Performance of Seismic Isolation Hardware under Service and Seismic Loading", *MCEER-07-0012*, MCEER, Buffalo, NY.

[8] Constantinou, M. C., Kalpakidis, I., Filiatrault, A. and Ecker Lay, R. A. (2011). "LRFD-Based Analysis and Design Procedures for Bridge Isolators and Seismic Isolators", *MCEER-11-0004*, MCEER, Buffalo, NY.

[9] Warn G. P., Whittaker, A. S. (2007). "Performance Estimates for Seismically Isolated Bridges", *MCEER-07-0024*, MCEER, Buffalo, NY.

[10] American Society of Civil Engineers (2017). "Seismic Evaluation and Retrofit of Existing Structures", *ASCE/SEI 41-2017*